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BACKWATER EFFECTS OF OPEN CHANNEL CONSTRICTIONS

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BACKWATER EFFECTS OF OPEN CHANNEL CONSTRICTIONS

H. J. Tracy[1] and R. W. Carter,[1] A.M. ASCE

SYNOPSIS

A method of computing the nominal backwater due to open channel constrictions was sought. A practicable solution has been accomplished which is based on an empirical discharge coefficient and a laboratory investigation of the influence of channel roughness. Also investigated as a part of the laboratory tests were effects of channel shape and constriction geometry. The solution involves the computation of water-surface drop through the constriction and the determination of a factor which is the ratio of backwater to water surface drop. This ratio is shown to be a function of channel roughness, percent of channel contraction, and constriction geometry.

INTRODUCTION

It is generally recognized that the introduction of a constriction in an open channel causes local, and in some instances, far reaching changes in the water surface profile. Evaluation of this "backwater" effect is of interest to those concerned with the location of artificial obstructions in natural channels. Highway departments have found such information desirable as a part of hydraulic studies made at proposed bridge sites.

This study was undertaken as an extension of an investigation [1, 2][2] recently completed by the U. S. Geological Survey, which was specifically concerned with the discharge characteristics of the constriction. Experimental data and certain computation procedures developed are directly applicable to the present study. Nomenclature common to the two investigations are used as defined for the earlier study.

Object of the Investigation

The object of this investigation was to study, by theoretical as well as by experimental means, the backwater effect of width constrictions in open channels. The ultimate objective was a practicable method of computation adapted to the evaluation of this effect.

Scope of the Investigation

This study was limited to an investigation of single-opening constrictions, and to steady, tranquil flows. The hydraulic characteristics of the channel were assumed to be uniform over the backwater reach. Thus, in the laboratory, the channels upstream and downstream from the constriction were made identical with respect to bed roughness, shape, and width. Variables in the laboratory investigation were discharge, depth of flow, channel roughness, and a limited variety of constriction geometries and channel shapes. It is

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2. Numbers in brackets refer to Appendix 11, References.

expected that the scope of this report will be extended to include multiple bridge openings as a part of continuing investigations.

Acknowledgments

This investigation was conducted as a part of the research program of the Water Resources Division of the U. S. Geological Survey. C. E. Kindsvater, Professor of Civil Engineering, Georgia Institute of Technology, as consultant to this program, made many helpful suggestions during the course of the study.

The authors wish to express their appreciation for the cooperation afforded by Professor W. M. Lansford and other faculty members of the Department of Theoretical and Applied Mechanics of the University of Illinois, and to W. D. Mitchell and J. H. Morgan of the Champaign office of the Geological Survey.

Description of the Problem

It is pertinent to a discussion of the backwater problem to compare the backwater condition with the normal, friction-controlled flow in the same channel reach without the constriction.

The backwater effect due to a constriction in a channel of mild slope is first manifest upstream from the constriction by a backwater profile of the M-1 variety [3] in which the velocities and consequently the rate of loss of flow energy is less than the normal. The beginning of this reach is designated by section 0 in Fig. 1. Near the constriction, at section 1 in the same figure, the central body of water begins to accelerate, whereas deceleration occurs along the outer boundaries, and a separation zone forms in the corners upstream from the constriction.

At the constriction, the flow is characterized by rapid acceleration in directions both along and normal to the stream lines. The average longitudinal water surface profile falls rapidly in this region. Within the constriction, the live stream contracts to a width somewhat less than the gross width of the opening and the spaces between the live stream and the constriction boundaries are occupied by eddying water. The extent of the contraction and consequent separation depends upon rate of flow, constriction and boundary geometry, and roughness.

Following the section of minimum live stream with (the *vena contracta*, section 2) is the beginning of an expansion process, which continues until the normal regime of flow has been re-established in the full width channel downstream (section 4). The reach from section 2 to section 4 is one of decelerated flow in which the average velocities and energy losses are greater than normal, due to the turbulence engendered by the expansion process. The length required to establish the normal regime downstream from the constriction is not known. Over the whole reach encompassed by the backwater effect, the total energy loss is the same as that for normal flow.

As a specific objective, the theoretical and laboratory phases of this analysis aimed at a description of the backwater effect in a limited region of the "backwater reach." Because of its use as a reference section in the earlier study [1], the nominal approach section (section 1, Fig. 1) was selected as the appropriate location for the measurement of the vertical extent of this effect.

Section 1 has been defined as the beginning of acceleration of the flow approaching the constriction. A distance upstream from the opening equal to one opening width (b) has been found to be an adequate approximation for the location of this section. Thus, the difference in water levels at section 1 between the normal and backwater profiles is the backwater measure adopted.

This difference in water levels has been designated by the symbol h_1^* on Fig. 1. Similarly, the backwater at the downstream side of the constriction (section 3)[3] is denoted h_3^* on the same figure.

A convenient dimensionless measure of backwater is the ratio $\frac{h_1^*}{\Delta h}$, where Δh is the difference in water surface elevation between section 1 and the downstream side of the constriction, section 3. The definition of Δh in terms of the discharge equation and certain coefficients is taken from the earlier study [1],

$$\Delta h = \frac{V_3^2}{2gC^2} - \alpha_1 \frac{V_1^2}{2g} + h_{f_{1-3}} \tag{1}$$

where C, the coefficient of discharge, is a function of shape and roughness of the approach channel, an appropriate Froude number, and the geometry of the constriction.

As illustrated in Fig. 1, Δh may be resolved into three components. From that figure,

$$\Delta h = h_1^* + h_3^* + \Delta h_n$$

where Δh_n is the friction loss between sections 1 and 3 in the non-obstructed channel. This equation, rearranged to give an explicit expression for the nominal backwater, h_1^*, becomes

$$h_1^* = \Delta h - h_3^* - \Delta h_n$$

and, in dimensionless form,

$$\frac{h_1^*}{\Delta h} = 1 - \frac{h_3^*}{\Delta h} - \frac{\Delta h_n}{\Delta h} \tag{2}$$

Here, Δh is determined by the discharge characteristics of the upstream reach. For a given value of Δh, the ratio $\frac{h_3^*}{\Delta h}$ is a measure of the relative magnitude of the recovery process, i.e., deceleration, and is a function of the downstream channel reach. The term $\frac{\Delta h_n}{\Delta h}$ is representative of the part played by friction in producing Δh as compared with the influence of acceleration.

The assumption is frequently made that the water surface immediately downstream from the constriction is the normal elevation, and that, neglecting friction losses, the backwater h_1^* is equal to the drop, Δh. Accordingly, the backwater ratio $\frac{h_1^*}{\Delta h}$ would then always have a value of 1.0. Equation (2) is useful in demonstrating that this assumption may be erroneous. The backwater

3. Section 3 is arbitrarily defined. The piezometric level at section 3 is measured in the relatively quiet zones of eddying fluid at the downstream side of the constriction. The water surface level thus measured has been shown to be equivalent to the elevation of the water surface at section 2 [1]. The area at section 3 is computed using the average depth and gross width of the opening at the downstream side.

ratio is equal to unity only when the normal friction loss and the downstream recovery of energy are small in comparison with Δh.

Approximate Solution for the Backwater Ratio

An approximate analytical solution for the backwater ratio can be obtained if it is assumed that normal boundary friction losses are zero [4]. In the following development of the approximate solution it is also assumed that the channel is horizontal, that the velocities in the live stream at section 2 are essentially constant, and that the piezometric head at section 3 is equivalent to the level at section 2, as shown in the earlier study [1]. See Fig. 2.

If V_2 is the average velocity of the live stream at section 2, and V_3 the average velocity at section 3 based on the gross area at section 3, the continuity relationships are:

$$Q = V_1 B y_1 = V_2 C_c b y_2 = V_3 b y_3 = V_4 B y_4 \tag{3}$$

From the momentum equation,

$$\frac{w b y_2^2}{2} + \frac{w(B - b)y_2^2}{2} - \frac{w B y_4^2}{2} = Q\rho(V_4 - V_2) \tag{4}$$

and from the energy equation,

$$y_1 + \frac{V_1^2}{2g} = y_2 + \frac{V_2^2}{2g} \tag{5}$$

Using the equality $y_2 = y_3$, and introducing the Froude number $F_3 = \frac{V_3}{\sqrt{g y_3}}$, equations (3) and (4) may be combined to yield:

$$\left(\frac{y_3}{y_4}\right)^3 - \frac{1 + 2\frac{b}{B}\frac{F_3^2}{C_c}}{2\left(\frac{b}{B}\right)^2 F_3^2}\left(\frac{y_3}{y_4}\right)^2 + \frac{1}{2\left(\frac{b}{B}\right)^2 F_3^2} = 0 \tag{6}$$

Solved simultaneously, equations (3) and (5) yield:

$$\left(\frac{y_1}{y_3}\right)^3 - \frac{2 + \left(\frac{F_3}{C_c}\right)^2}{2}\left(\frac{y_1}{y_3}\right) + \frac{F_3^2\left(\frac{b}{B}\right)^2}{2} = 0 \tag{7}$$

Equations (6) and (7) for this approximate solution describe $\frac{y_3}{y_4}$ and $\frac{y_1}{y_3}$ implicitly in terms of channel contraction ratio, $\frac{(b)}{B}$, a Froude number, and the coefficient of contraction, C_c.

In the development [1] of an empirical expression for the coefficient of discharge C, that coefficient was shown to be primarily a coefficient of contraction. A comparison of the expression for C with an equation derived theoretically for the discharge through a constriction leads to the relationship:

$$C = \frac{C_c}{\sqrt{K + \alpha_2}}$$

in which K is used to describe eddy losses in the upstream separation zone, which are normally very small. The velocity distribution coefficient α_2 is commonly assumed to be unity. From dimensional analysis [1], C can be shown to depend upon a Froude number, the geometries of the upstream channel and of the constriction, and upon an appropriate depth.

Thus, C_c may be represented by the coefficient C in equations (6) and (7). The variation of C with the variables named above is shown graphically in reference [2] in which C is defined for several practical constriction types.

Two solutions for the backwater ratio are shown in Figs. 3 and 4. For these solutions, equations (6) and (7) were solved for $\frac{y_3}{y_4}$ and $\frac{y_1}{y_3}$ first by choosing constriction and channel geometries for which C = 1.00 for a full range of values of F and $\frac{b}{B}$. A similar solution was made selecting C for constriction geometries having minimum contraction coefficients, those for vertical faced constrictions with square edged entrances.

From these two solutions for $\frac{y_1}{y_3}$ and $\frac{y_3}{y_4}$, the backwater ratio for this approximate solution may be computed. For the frictionless condition, and with no bottom slope, $y_{1_n} = y_4$: Hence:

$$\frac{h_1^*}{\Delta h} = \frac{\frac{y_1}{y_3}\frac{y_3}{y_4} - 1}{\frac{y_1}{y_3}\frac{y_3}{y_4} - \frac{y_3}{y_4}}$$

In Figs. 3 and 4 the description of the degree of channel contraction has been modified to be expressed as $\underline{m} = (1 - \frac{b}{B})100$ instead of the $\frac{b}{B}$ ratio indicated in equations (6) and (7).

For this special solution, it will be noted from figures 3 and 4 that the Froude number has little effect on the ratio $\frac{h_1^*}{\Delta h}$, and that this ratio is dependent primarily on $\underline{m}$, with C_c exerting a secondary influence. The effect of a decrease in C_c is to increase $\frac{h_1^*}{\Delta h}$, but even when C_c is varied through its maximum practical range, as it was in the two solutions, its effect is rather small.

The Laboratory Investigation

Exploratory tests in the initial phase of this study were made in the hydraulics laboratory of the Georgia Institute of Technology. These tests established the relative importance of the variables involved and indicated the desirability of conducting further tests in a flume of greater length than that used for the exploratory tests.

Thus, arrangements were made for the use of a flume in the A. N. Talbot hydraulics laboratory of the University of Illinois at Urbana, Illinois. This flume is rectangular in cross section, 164 feet long, 5 feet wide, and 4.75 feet deep. The floor of the flume is level. A maximum discharge of 14 cfs is provided by the laboratory's re-circulating system. Discharges are measured by means of a 12-inch bend meter in the supply pipe line. Baffles were used to obtain uniform velocities downstream from the supply entrance.

The beginning of the test reach in the flume was about 15 feet from the supply pipe outlet. The depth of flow in the flume was regulated by means of an adjustable tailgate located 148 feet downstream from the beginning of the test section. Except in the vicinity of the constriction, water surface elevations were read at 10 foot intervals along the length of the flume by means of fixed point gages set over the center of the flume. At the constriction, water-surface levels were read by means of a movable point gage which traversed the width as well as the length of the flume. Constrictive elements were of aluminum plate and plywood. For all tests, the constriction was located 55 feet downstream from the beginning of the test section.

Boundary roughness was created by means of various arrangements of chain-link fencing, and expanded metal. The cross-sectional shape of the test section was altered by means of false floors, using smooth transite sheets and redwood lumber.

<u>Methods of Testing</u>

The general test procedure for backwater measurements consisted of making two complete sets of surface-level observations over the full length of the test section. This was done, first, with the constriction in place and, second, with the constriction removed.

Tests on the rectangular flume were made with four degrees of channel roughness. The concrete floor and sides of the basic flume provided a condition of minimum roughness corresponding to a Manning's $\underline{n}$ of .012 which was constant over the range of depths tested. A second degree of roughness was created by covering the flume floor uniformly with 2-inch chain-link, diamond-mesh, wire fencing. The resulting $\underline{n}$ as determined in the laboratory was 0.023. By adding expanded-metal sections which projected 2-1/2 inches above the chain-link fence, a value of $\underline{n}$ of .050 was measured at a flow depth of one foot. For this condition of roughness, $\underline{n}$ decreased slightly at greater depths, and was considerably greater at depths less than one foot.

For testing the effect of a change in shape of channel cross section, a false bottom was built into the flume. The dimensions of this alternate arrangement are shown in Fig. 5. A limited number of tests were made in this flume, for which Manning's $\underline{n}$ was computed as .010.

Analysis of Experimental Data

The laboratory phases of the investigation was first concerned with the measurement of the backwater ratio $\frac{h_1^*}{\Delta h}$ in a uniform rectangular flume at various degrees of bed roughness, using vertical-faced constrictions with square-edged abutments. Using the curves defined by this data as base, or standard values, other constriction and channel geometries were tested and the variation of the backwater ratio then determined as a departure from this base.

The Backwater Ratio for the Base Condition

Sufficient tests were made to describe the backwater ratio for vertical-faced constrictions with square-edged abutments in the rectangular flume for three degrees of channel roughness, ranging from smooth to fairly rough. The results, plotted separately for each of the three roughness conditions, are shown in Figs. 6, 7, and 8. For convenience, these three curves have been summarized in Fig. 9, omitting the Froude number as a variable because of its minor effect. Also shown on this figure are curves resulting from the approximate analysis. It is apparent from the figure that the approximate solution is an aid in describing the shape and limits of the experimental curves.

Important during this series were tests made to isolate the influence of depth of flow, $\frac{y_3}{b}$; and of constriction length, $\frac{L}{b}$. With all other variables held constant, a variation of these parameters between tests proved to have no effect on the backwater ratio.

In this study, the width ratio $\frac{b}{B}$ (or $1 - \frac{b}{B}$) has been sufficient up to this point to describe the percent of channel contraction. However, when irregular channels of non-uniform roughness are considered, this definition of the relative degree of constriction imposed is no longer valid. By interpreting $\underline{m}$ as the proportion of total flow entering laterally into the contracted stream, a useful concept is gained. This may be stated thus:

$$\underline{m} = (1 - \frac{q}{Q})100$$

Where q is that portion of the total discharge Q occupying an area of width b in the total cross section upstream from the constriction. By computing the ratio $\frac{q}{Q}$ as a ratio of hydraulic conveyances, this definition may be stated:

$$\underline{m} = (1 - \frac{K_q}{K_Q})100$$

where K_q is the conveyance of that portion of the approach channel occupied by the discharge q, and K_Q is the conveyance of the total section. For the rectangular channel of uniform roughness characteristics heretofore considered, this expression reduces to the previous of $\underline{m}$, that is, $(1 - \frac{b}{B})100$.

In discussing equation (2), it was pointed out that the backwater ratio is influenced by the channel characteristics of both upstream and downstream reaches, as well as by the constriction geometry. It is reasonable to believe that the variable, $\underline{m}$, descriptive of channel shape and roughness only at channel section upstream from the constriction, is not necessarily always an adequate measure of channel geometry in the downstream reach. Actually, as tested in the laboratory, the channels were identical in shape and roughness in both reaches; therefore results developed here should not be applied to channels in which these two reaches are significantly different.

The Effect of Channel Roughness

Despite the limitations of Manning's $\underline{n}$ as a measure of channel roughness, its use in this study is not a serious shortcoming, primarily because roughness is relatively unimportant as a factor in the determination of the backwater

ratio. This is shown in Fig. 10, which is an alternative presentation of the data shown in Fig. 9, replotted to show more clearly the variation of $\frac{h_1^*}{\Delta h}$ with $\underline{n}$. This figure indicates that at an $\underline{n}$ of about .050 the limit of the change in the backwater ratio due to channel roughness has been reached.

It is of interest to note that h_1^* increases as $\underline{n}$ increases. This may be shown by an examination of equation (1) and Fig. 10. Equation (1) indicates an increase in Δh with $\underline{n}$. Fig. 10 demonstrates an increase in $\frac{h_1^*}{\Delta h}$ with $\underline{n}$. It is thus evident that h_1^* must also increase with $\underline{n}$. Similiarly, it may be shown that h_3^* decreases as $\underline{n}$ increases.

The Effect of Channel Shape

Twelve tests were made using the flume shown in Fig. 5 to determine the effect of a single variety of complex channel cross section on the backwater ratio. Vertical-faced constrictions with square-edged abutments were used as before to permit these tests to be compared directly with those made in the rectangular channel using the same type of constriction. Manning's $\underline{n}$ for this channel was computed as .010. These twelve tests are plotted on the curves developed for the rectangular channel, and are shown in Fig. 11. Taking into consideration the differences in channel roughness, the agreement between these tests and those made in the concrete rectangular flume ($\underline{n}$ = .012) is good. This has been taken as evidence that the influence of cross-sectional shape is incorporated in the variable $\underline{m}$.

The Effect of Constriction Geometry

As suggested earlier, the effect of constriction type on the backwater ratio has been analysed as a systematic variation from the base curves of Fig. 9. Necessary to this treatment is an index descriptive of those features of geometry which influence flow phenomena in the backwater reach. It is reasonable to use the coefficient C for this purpose, since C is also primarily a function of constriction geometry.

A number of tests were made in the rectangular, uniformly smooth concrete flume using constrictions providing less abrupt entrances than those of the base type. For these tests, backwater ratios were obtained which were smaller than those shown by the base curves of Fig. 9. As a measure of the variation between the tests and the base curves, each of the backwater ratios of the tests was divided by the corresponding base ratio, selected from Fig. 9. The resulting factor, k_c, is thus an expression for the departure of the tested condition from that of the base condition.

By dividing the coefficient C applicable to the tested constriction by a coefficient C appropriate to a vertical-faced, square-edged constriction with an identical $\underline{m}$, a factor which correlates with k_c is obtained. The variation of k_c with this factor is shown in Fig. 12, in which the plotted points represent tests made on other than base type constrictions. In effect, this figure shows the variation in backwater ratio due to constriction geometry as a function of the coefficient of discharge.

Computation Procedure

This study has defined a nominal backwater from open channel constrictions, which has been referred to as h_1^* (refer to figure 1). This backwater is the difference between the normal and the constricted channel water surface profiles at an arbitrarily chosen section, section 1. This backwater index has

been divided by a known quantity, Δh, to give a dimensionless measure of the backwater effect.

When integrated with an earlier study which investigated the discharge characteristics of open channel constrictions, and using the concepts and charts developed during that study, the results of the present analysis may be used to predict h_1^* for constricted natural channels, within the scope of this study. This additional material is to be found in references [1, 2].

The backwater, h_1^*, is computed as the product of $\frac{h_1^*}{\Delta h}$ and h. The difference in piezometric heads between section 1 and 3 for the constricted channel, Δh, may be computed from equation (1). The solution of this equation depends upon a knowledge of the channel properties at section 1 and 3, and upon the evaluation of the coefficient C.

The backwater ratio itself, $\frac{h_1^*}{\Delta h}$, has been shown by laboratory data to be a function primarily of degree of channel contraction. The influences of bed roughness and constriction geometry are secondary. Variables characteristic of the flow, as Froude number and depth, are largely unimportant in their effect on this ratio.

In application, $\frac{h_1^*}{\Delta h}$ is selected from figure 9, appropriate to the bed roughness and degree of contraction of the channel. Compatible with the conditions under which the laboratory tests were made, this roughness must be representative of an average in the channel reaches both upstream and downstream from the constriction. Some latitude is tolerable in the precision of the selection, because of the relative insenstivity of $\frac{h_1^*}{\Delta h}$ with $\underline{n}$. Computation of $\underline{m}$ for channel of non-uniform roughness is described in reference [2].

After $\frac{h_1^*}{\Delta h}$ of the previous step has been chosen, it is adjusted for constrictions geometry effect by the factor k_c, obtained from figure 12. This correction factor is a function of a $\frac{C}{C_{base}}$ ratio; the computation of which has been outlined earlier, and the degree of contraction $\underline{m}$.

The adjusted backwater ratio may then be multiplied by Δh to give h_1^*.

APPENDIX I

NOTATION

A area of channel cross section

b width of opening

B width of channel

C coefficient of discharge

C_c coefficient of contraction; ratio of area of contracted stream to area of opening

F Froude number; a dimensionless flow parameter for gravity-controlled phenomena

g acceleration due to gravity

h piezometric head; sum of elevation and pressure heads

h^* a difference in piezometric heads involving normal and constricted channel flow

K conveyance; the quantity $\frac{1.49}{n} AR^{\frac{2}{3}}$ in Manning's formula for open channel flow. Also, an energy loss coefficient

k_c an adjustment coefficient; ratio of backwater ratio to the backwater ratio for the base condition

L length of constriction, measured parallel to flow

m channel contraction ratio

n roughness coefficient in the Manning formula for open channel flow; also used as a subscript to denote "normal"

Q volume rate of flow; total discharge at a channel cross section

V average velocity; ratio of total discharge to total area of a cross section

w specific weight; weight per unit volume

y depth of flow referred to average bottom elevation of cross section

Δ a symbol denoting "change" or "difference"

ρ density; mass per unit volume

APPENDIX II

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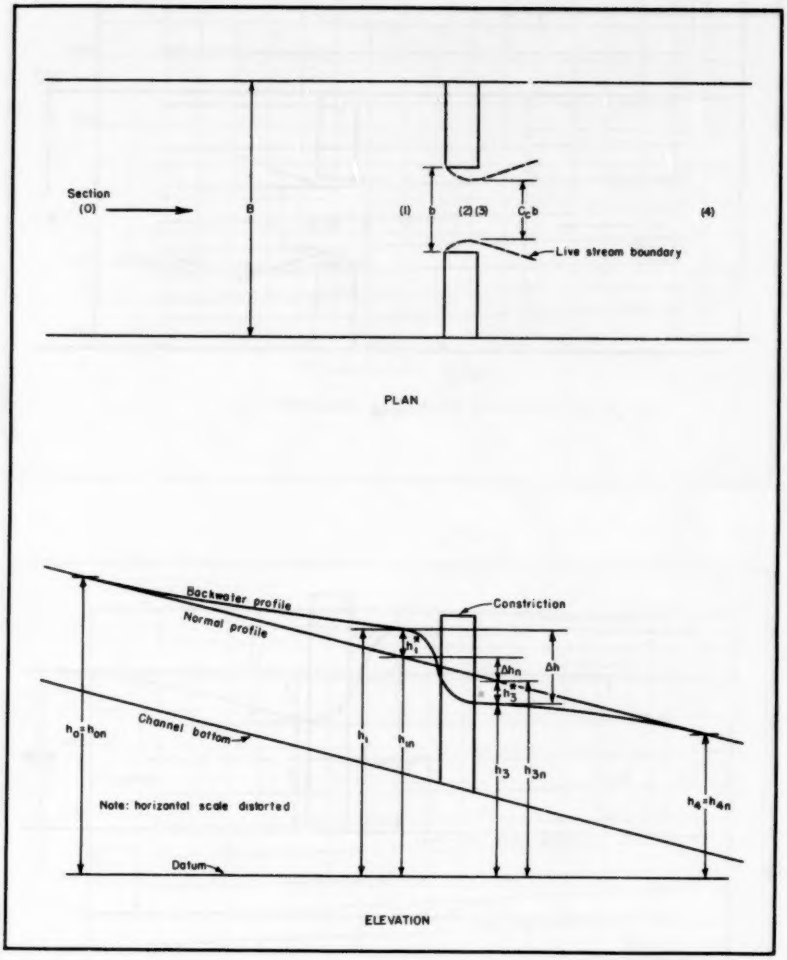

FIG. 1–DEFINITION SKETCH OF THE BACKWATER REACH

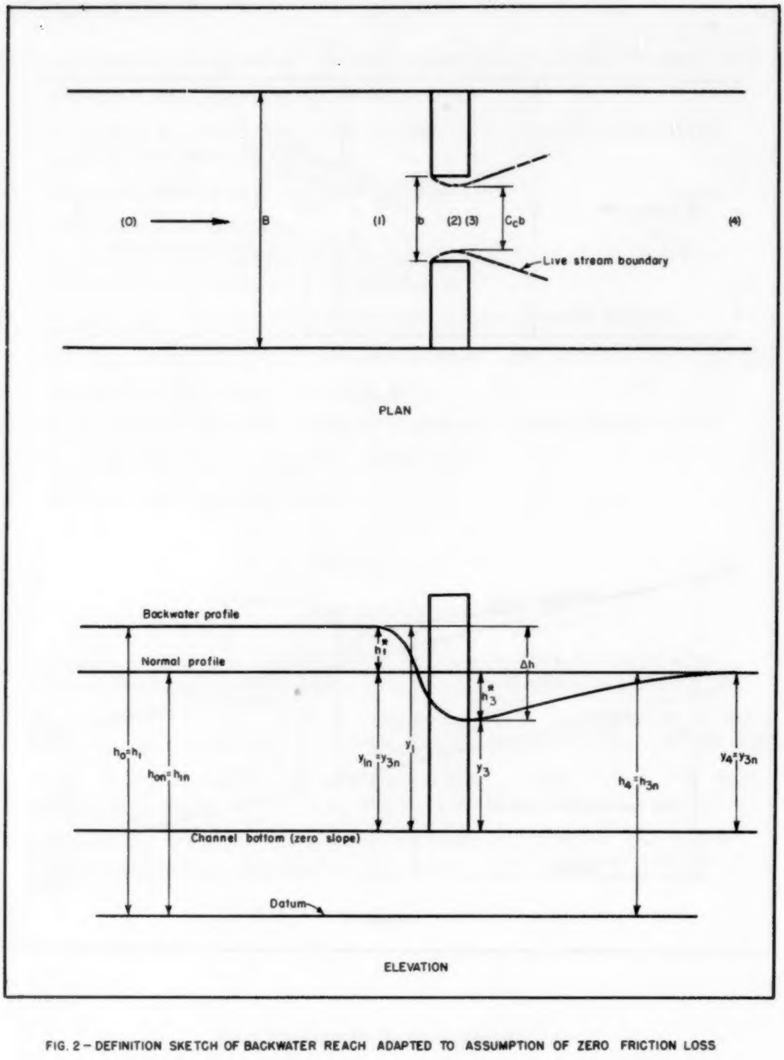

FIG. 2 – DEFINITION SKETCH OF BACKWATER REACH ADAPTED TO ASSUMPTION OF ZERO FRICTION LOSS

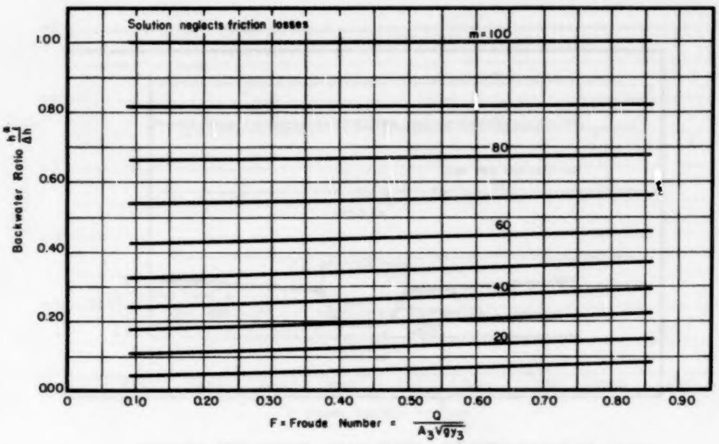

FIG. 3–APPROXIMATE SOLUTION FOR BACKWATER RATIO ($C_c = 1.0$)

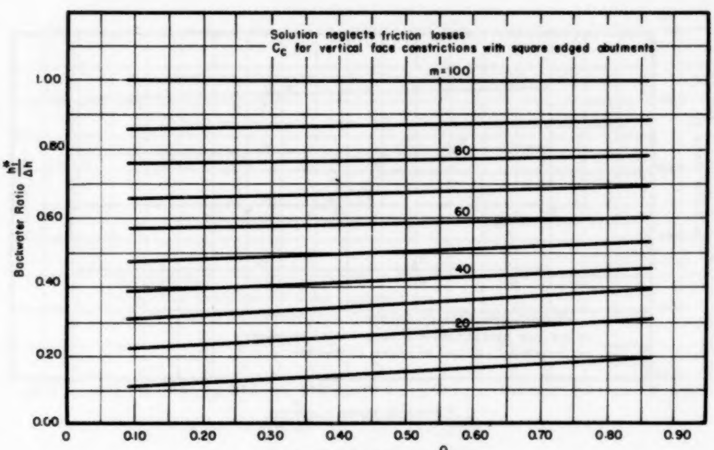

FIG. 4– APPROXIMATE SOLUTION FOR BACKWATER RATIO ($C_c = C$)

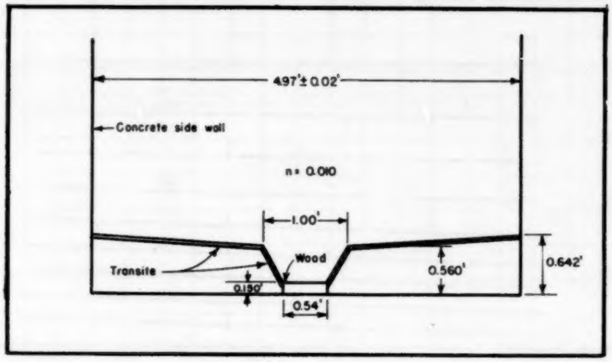

FIG. 5 – CROSS SECTIONAL VIEW OF FLUME ARRANGEMENT (ILLINOIS)

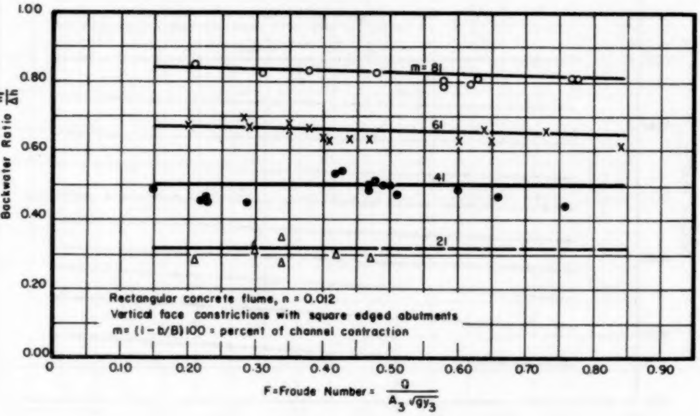

FIG. 6 – MEASURED VALUES OF THE BACKWATER RATIO, n = 0.012

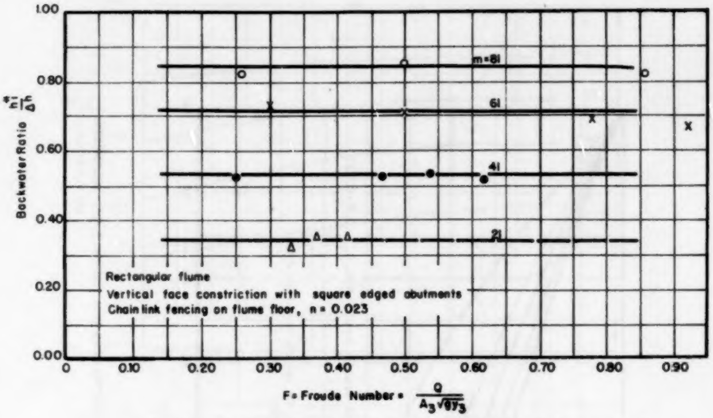

FIG. 7— MEASURED VALUES OF THE BACKWATER RATIO, n = 0.023

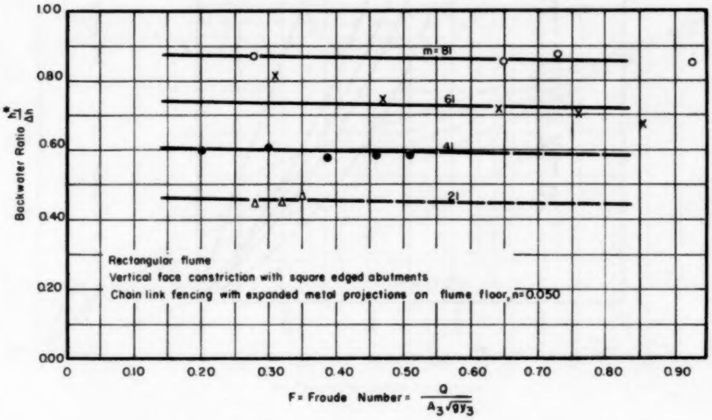

FIG. 8 – MEASURED VALUES OF THE BACKWATER RATIO, n = 0.050

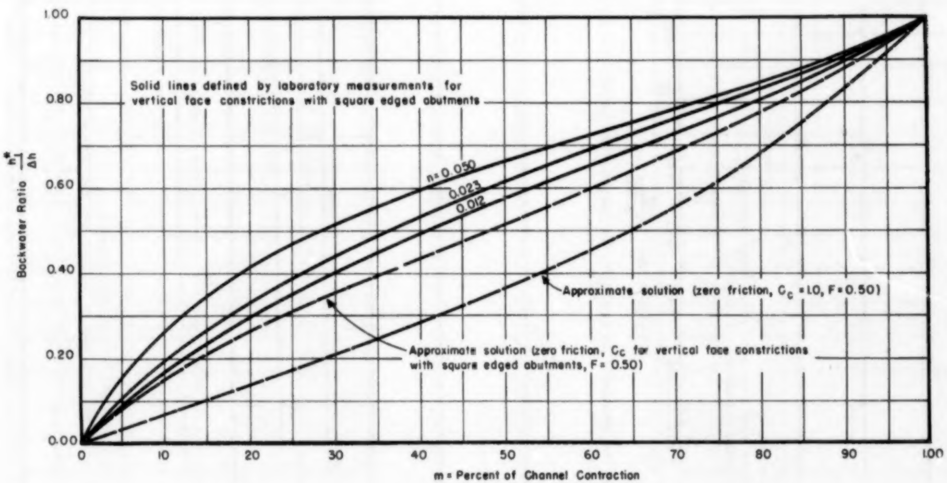

FIG. 9 – SUMMARY CURVES OF THE BACKWATER RATIO FOR VERTICAL FACE CONSTRICTIONS WITH SQUARE EDGED ABUTMENTS

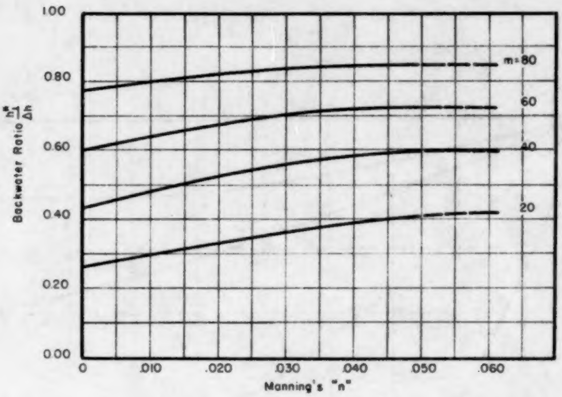

FIG. 10– THE EFFECT OF CHANNEL ROUGHNESS ON THE BACKWATER RATIO, VERTICAL FACE CONSTRICTIONS WITH SQUARE EDGED ABUTMENTS

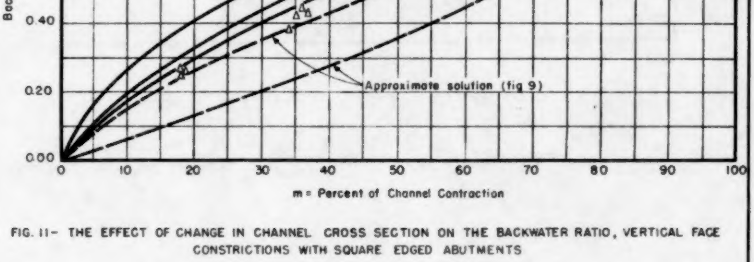

FIG. 11– THE EFFECT OF CHANGE IN CHANNEL CROSS SECTION ON THE BACKWATER RATIO, VERTICAL FACE CONSTRICTIONS WITH SQUARE EDGED ABUTMENTS

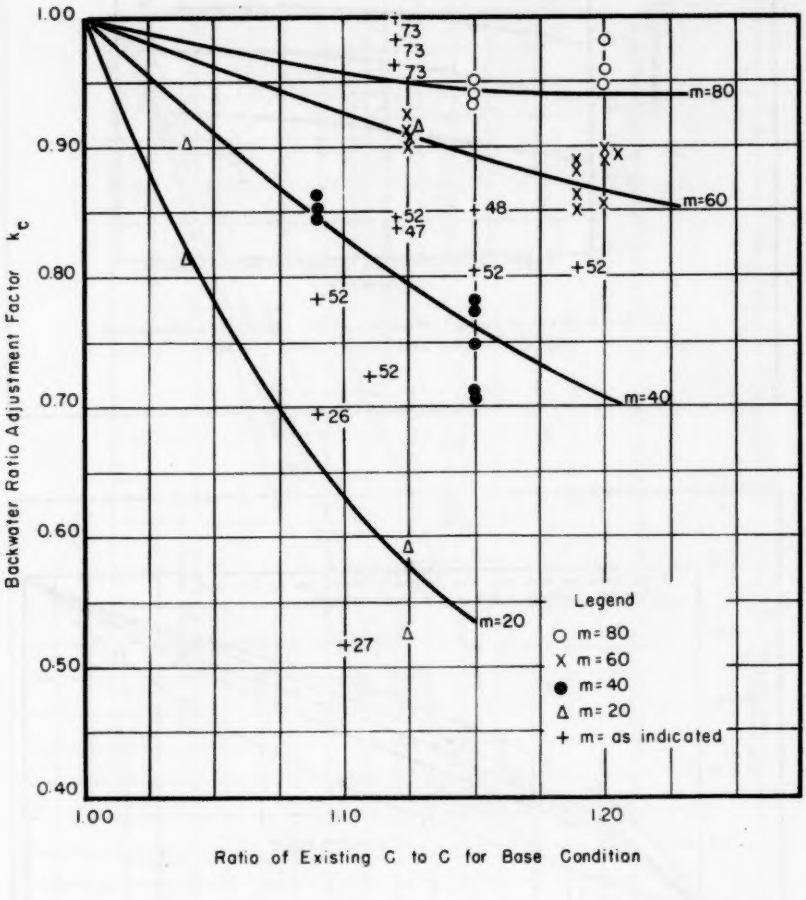

FIG. 12 – THE EFFECT OF CONSTRICTION GEOMETRY ON THE BACKWATER RATIO